# Time-Resolved Ultraviolet Spectroscopy of the SW Sex Star DW UMa: Confirmation of a Hidden White Dwarf and the UV Counterpart to Phase 0.5 Absorption Events [1]

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## ABSTRACT

We present time-resolved, ultraviolet (UV) spectroscopy of the SW Sex star DW UMa in the high state. We confirm that, shortward of 1500 Å, the high-state, UV continuum level is lower than the white dwarf (WD)-dominated low-state level. We also do not see the WD contact phases in the high state eclipse light curves. These results confirm our earlier finding that the WD in this system is hidden from view in the high state. Based on this, we caution that eclipse mapping of high-inclination SW Sex stars in the high state may yield incorrect or misleading results. In the context of DW UMa, we demonstrate explicitly that distance estimates obtained by recent eclipse mapping studies cannot be reconciled with the WD-dominated low-state spectrum. We also show that the fluxes of the UV emission lines in the high state drop near orbital phase 0.5. This is the first detection of a UV counterpart to the class-defining phase 0.5 absorption seen in the optical emission lines of SW Sex stars.

*Subject headings:* accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual: DW UMa

## 1. Introduction

The SW Sex stars are a sub-class of nova-like cataclysmic variable stars (CVs). As such, they are interacting binary systems containing a Roche-lobe filling secondary star that

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is losing mass to an accretion disk around a white dwarf (WD) primary. The SW Sex classification was first suggested by Thorstensen et al. (1991), building on earlier work by Downes et al. (1986), Honeycutt, Schlegel & Kaitchuck (1986), Shafter, Hessman & Zhang (1988), and Szkody & Piché (1990). The key common features of the four founding members of the class – SW Sex, DW UMa, V1315 Aql and PX And – were transient, central absorption features in the Balmer and He I lines near orbital phase 0.5. Also, the radial velocity curves derived from these lines generally showed significant phase lags with respect to the orbital motion of the WD. Other common spectroscopic properties within the class are single-peaked optical emission lines at orbital phases well away from 0.5 (rather than the double-peaked lines expected from edge-on accretion disks); weak eclipses of the Balmer and He I lines; and He II features that do appear to track the WD motion and are more deeply eclipsed than the low-ionization lines.

The continuum eclipses of high-inclination SW Sex stars are also unusual. They are considerably more V-shaped than those of "ordinary" eclipsing, non-magnetic nova-like CVs (such as UX UMa). If the eclipsed light is assumed to be produced by a geometrically thin, optically thick disk, this immediately implies that the outer disk contributes relatively more light in SW Sex stars than in other CVs. Unsurprisingly, eclipse mapping experiments have therefore invariably inferred very flat surface brightness (and hence effective temperature) distributions across the disks of SW Sex stars (e.g. Rutten, van Paradijs & Tinbergen 1992; Baptista, Steiner & Horne 1996; Baptista et al. 2000; Groot, Rutten & van Paradijs 2001). This contrasts starkly with the theoretically expected temperature distribution, which drops as $R^{-3/4}$ with radius.

Against this background came the first time-resolved, ultraviolet (UV) observations of a bona-fide SW Sex star — DW UMa – with the *Hubble Space Telescope* (Knigge et al. 2000; Araujo-Betancor et al. 2003). These fortuitously occurred during a low state of the system, during which the optical light was suppressed by approximately 3 mags relative to the normal high state. Such low states are thought to be caused by a temporary reduction or cessation of the mass supply from the donor star. The UV observations were broadly consistent with this scenario, inasmuch as the low state UV spectrum appeared to be dominated by the hot ($T_{eff} \simeq 50,000$ K) WD primary. However, a surprise was that the far-UV flux level was higher in the low-state HST data than in high-state UV observations obtained with the *International Ultraviolet Explorer* (IUE). This implies that the WD in DW UMa is hidden from view in the high state. We therefore suggested that the disk in this high-inclination system ($i \simeq 82^o$; Araujo-Betancor et al. 2003) is self-occulting in the high state, i.e. that the disk rim obscures our view of the WD and the central disk regions.

If the WD and inner accretion flow in high-inclination SW Sex stars are permanently occulted, then this needs to be accounted for in any realistic model for these systems. After all, the majority of confirmed SW Sex stars are eclipsing [3], which indicates that geometric effects influence our ability to even recognize members of the class. It is therefore important to confirm the result of Knigge et al. (2000), not least to rule out cross-calibration errors between the high-state IUE data and the low state-HST observations.

Here, we present a first look at time-resolved, HST observations of DW UMa in the high state, which were obtained using exactly the same observational set-up as the low-state data. The results confirm conclusively that the WD in this system is hidden from view in the high state and show, for the first time, that the UV lines take part in the phase 0.5 absorption events that are the key optical characteristic of the SW Sex class.

## 2. Observations and Analysis

Our high-state HST observations of DW UMa took place on April 4, 2004 and covered just over two complete cycles of DW UMa's 3.28 hr orbital period. We used the acquisition image (obtained with the STIS CCD and the F28X50LP filter) to estimate an optical (roughly R-band) magnitude of 14.1. Thus DW UMa was clearly in its normal high state during these observations (see Stanishev et al. [2004] for a long-term light curve). Our UV spectroscopy was carried out using the $52'' \times 0''.2$ slit, the FUV-MAMA detector, and the G140L grating. This combination covers 1150 Å – 1720 Å at a resolution of $\simeq 1$ Å (FWHM). TIME-TAG mode was used throughout, allowing us to split the data into suitable subexposures a posteriori. These subexposures were then calibrated using the STIS pipeline, using the reference files available in June 2004. For consistency in comparing low-state and high-state data, we also recalibrated the low-state observations obtained in 1999 with the latest version of the pipeline and reference files. The absolute flux scale of our spectra should be accurate to about 4%.

Calibrated UV spectra from both states are shown and compared in Figure 1. Both spectra were extracted from data taken well-away from eclipse when the flux was relatively constant (both high and low state display considerable UV variability). The overall appearance of the high-state HST spectrum – line-dominated, with a flat continuum – is very similar to that of the high-state IUE spectrum shown by Knigge et al. (2000). The continuum flux levels are also similar, and we find again that, shortward of 1500 Å, the low-state UV spectrum has a higher continuum flux level than the high-state spectrum. In fact, at the shortest wavelength, the ratio of low-state to high-state continuum flux exceeds a factor of

[3]See DWH's *Big List of SW Sex Stars* at http://spider.ipac.caltech.edu/staff/hoard/biglist.html.

four. Thus even allowing for the possibility that our view of the lower half of the WD might be blocked by an optically thick disk in the high state (and that this disk might somehow avoid radiating in the UV), the high-state UV flux is inconsistent with the assumption that our view of the WD at the centre of the disk is unimpeded.

In Figure 2, we additionally show continuum light curves extracted from our TIME-TAG data, focusing particularly on the eclipses. The data were phase-folded using the ephemeris of Stanishev et al. (2004), and the vertical lines mark the WD contact phases measured by Araujo-Betancor et al. (2003). There are no obvious, repeatable steps in the light curves at or near the predicted WD ingress/egress intervals. This is consistent with the low UV flux level and confirms that the WD in DW UMa is hidden in the high state.

The top panel of Figure 2 also shows the continuum-subtracted light curve of the strongest line in the spectrum, C IV. This reveals that (i) the line is much more weakly eclipsed than the adjacent continuum, and (ii) in both orbital cycles, the line flux reaches a minimum near phase 0.5 (the continuum light curve actually appears to display a similar morphology in the second cycle). In order to allow a closer examination of these effects, we present in Figure 3 the high-state UV spectra binned in orbital phase. The key point to note from this is that the line fluxes of all strong UV transitions are suppressed near orbital phase 0.5. This is the first detection of a UV counterpart to the class-defining phase 0.5 absorption seen in the low-ionization optical emission lines of SW Sex stars. The effect appears to be weakest in He II 1640 Å, which is consistent with the absence or weakness of 0.5 absorption in the He II 4686 Å lines of SW Sex stars.

## 3. Discussion and Conclusions

Our UV observations establish conclusively that the WD in DW UMa is hidden from view in the normal high state. We still believe that the simplest way to explain this finding is to postulate the existence of a self-occulting accretion disk in this system. However, independent of any specific theoretical framework, it is clear that the accretion flow cannot even approximately be described as 2-dimensional, and that any viable model or description of the system must account somehow for the observed occultation. It is therefore more difficult to use the eclipses to gain insight into the nature of the high-state accretion flow (but not impossible: see Hellier & Mason [1989] for an example in the context of low-mass X-ray binaries). By contrast, all existing high-state eclipse mapping studies of DW UMa (and other SW Sex stars) have assumed that the disks in these systems are fully visible. [4] In our view, the immediate corollary of this is that results inferred from these studies should be regarded with caution.

We suspect that the short distance estimates for DW UMa suggested in recent eclipse mapping studies ($d \simeq 300$ pc; Bíró 2000; Stanishev et al. 2004) are a manifestation of this problem. Such a short distance is inconsistent with the estimate d =590 ± 100 pc obtained from fitting the low-state spectrum with a WD model atmosphere and also with the estimate d = 930 ± 160 pc obtained from Bailey's method (Araujo-Betancor et al. 2003). We have considered whether the WD-dominated low-state spectrum can in some way be reconciled with a distance of 300 pc. We thus show in Figure 1 three $\log g = 8$ DA WD models (calculated as in Gänsicke, Beuermann & de Martino [1995]) for different effective temperatures ($T_{eff}$). The models have been scaled to match the observed low-state spectrum at 1480 Å, have not been convolved with the instrumental line spread function and have also not been rotationally broadened. Thus the width of Lyman $\alpha$ in the models is a lower limit.

The $T_{eff} = 50,000$ K model was chosen to represent the best-fitting WD model found by Araujo-Betancor et al. (2003). This model fits the data fairly well away from metal lines and requires a distance (d = 540 pc) in line with our previous estimate (this assumes a fully visible WD and the best-bet WD radius found by Araujo-Betancor et al.). By contrast, the eclipse-mapping distance of d = 300 pc requires a WD model with $T_{eff} \simeq 28,000$ K. This model produces much too wide a Lyman $\alpha$ feature and can be ruled out immediately. If only half the WD were visible in the low state (e.g. because the lower half is blocked by a disk), d = 300 pc corresponds to $T_{eff} \simeq 37,000$ K. This model still overpredicts the width of Lyman $\alpha$ significantly and can also be ruled out.[5]

Is it plausible that the flat-disk assumption in eclipse mapping studies might cause distances to be underestimated? Roughly speaking, these estimates are based on the color and brightness of the pixels in a disk map, and assuming these to radiate as blackbodies

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[4]In their eclipse mapping study, Stanishev et al. (2004) comment on the occultation problem and suggest that the optically thick base of an accretion disk wind may hide the WD in DW UMa. But this scenario is just a specific incarnation of a self-occulting disk atmosphere with unknown geometry, and thus still violates the assumption of full disk visibility. It is also worth recalling here the work of Rutten (1998), who shows that the application of a standard (flat-disk) eclipse mapping code to a flared disk can give reasonable results, *as long as the disk is not self-occulting*. Once the inner disk is no longer visible, the method produces artificially flat radial temperature distributions.

[5]We actually do not consider this to be a physically realistic model: if an optically thick disk were present in the low state, it would be strongly irradiated and therefore hot. It should then emit copious amounts of UV radiation, but no disk contribution is seen.

(BBs) or stellar atmospheres (SAs). If the disk is assumed to be flat, the flux from each pixel then scales as $\cos i/d^2$ (modulo a correction for limb-darkening); this allows $d$ to be estimated. However, most other accretion structures (e.g. a disk rim) would be *less* strongly foreshortened when averaged over the visible projected area of the structure. The flat-disk scaling will yield erroneous results in such cases. To see this, consider an accretion flow element that is seen more face-on than the pixel representing it in a flat-disk eclipse map. The temperature of this element/pixel is roughly fixed by its color. If a $\cos i$ foreshortening factor is incorrectly applied to this element/pixel by the eclipse mapping algorithm, the distance inferred from it will be an underestimate. After all, the excessively foreshortened disk map pixel must still produce the observed flux. This is only possible if it is brought closer than the face-on accretion flow element it represents. Thus the flat disk assumption might indeed cause distances to be underestimated systematically. When this happens, the color-magnitude diagrams constructed from disk map pixels will probably also show large scatter about the expected BB/SA relations (since different accretion flow elements are likely to have different foreshortening factors). This would appear to be the case in DW UMa (see Figure 5 in Bíró 2000).

As a final note on the distance issue, we acknowledge that the distance estimates based on Bailey's method and the WD-dominated UV spectrum are themselves only marginally consistent with each other (see discussion in Araujo-Betancor et al. 2003). However, these estimates are much more easily reconciled with each other than with the short eclipse mapping distance. We have already shown explicitly that a WD at 300 pc produces a much broader Lyman alpha feature than is observed. But this distance would also require an unrealistically late spectral type for the secondary (to avoid over-predicting the low-state, mid-eclipse K-band flux).

Turning to our detection of a UV counterpart to the phase 0.5 absorption events seen in optical spectra of SW Sex stars, we note that this could not necessarily have been expected: the formation mechanism of these high-ionization (and mostly resonance) lines might be expected to differ significantly from that of the optical low-ionization lines where the effect is normally seen. Strictly speaking, we cannot yet claim that the UV lines are affected by genuine *absorption* near phase 0.5: none of the lines exhibit dips below continuum level at this phase, so the data are also consistent with an intrinsic weakening of the lines. However, the Balmer lines of SW Sex stars generally also do not show absorption below continuum, although this effect has been seen in the He I lines of several systems (e.g. Szkody & Piché 1990). On balance, we are therefore inclined to ascribe the weakening of the UV lines to the same absorbing medium that is affecting the optical lines. Given the wide range of transitions affected, this probably implies non-uniform physical conditions in the absorbing material.

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## REFERENCES

Araujo-Betancor, S., et al. 2003, ApJ, 583, 437

Baptista, R., Silveira, C., Steiner, J. E., & Horne, K. 2000, MNRAS, 314, 713

Baptista, R., Steiner, J. E., & Horne, K. 1996, MNRAS, 282, 99

Bíró, I. B. 2000, A&A, 364, 573

Downes, R. A., Mateo, M., Szkody, P., Jenner, D. C. and Margon, B. 1986, ApJ, 301, 240

Gänsicke, B. T., Beuermann, K. & de Martino, D. 1995, A&A 303, 127

Groot, P. J., Rutten, R. G. M., & van Paradijs, J. 2001, A&A, 368, 183

Hellier, C. & Mason, K. O. 1989, MNRAS, 239, 715

Honeycutt, R. K., Schlegel, E. M. and Kaitchuck, K. H. 1986, ApJ, 302, 388

Knigge, C., Long, K. S., Hoard, D. W., Szkody, P., & Dhillon, V. S. 2000, ApJ, 539, L49

Rutten, R. G. M. 1998, A&AS, 127, 581

Rutten, R. G. M., van Paradijs, J. & Tinbergen, J. 1992, A&A, 260, 213

Shafter, A. W., Hessman, F. V. and Zhang, E-H. 1988, ApJ, 327, 248

Stanishev, V. et al. 2004, A&A, 416, 1057

Szkody, P. and Piché, F. 1990, ApJ, 361, 235

[6]http://www.pa.uky.edu/~peter/atomic

Thorstensen, J. R., Ringwald, F. A., Wade, R. A., Schmidt, G. D., & Norsworthy, J. E. 1991, AJ, 102, 272

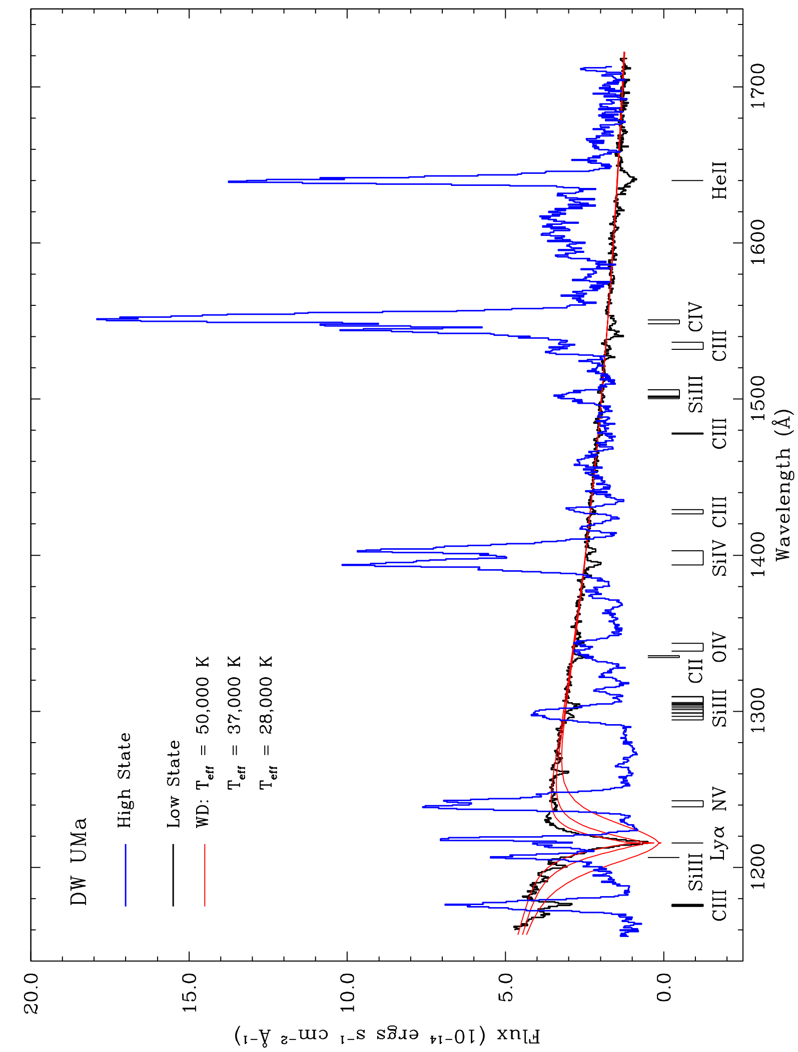


Fig. 1.— DW UMa's out-of-eclipse UV spectrum in the high (blue line) and low state (black line). Suggested line identifications for the strong features in the spectra are given. Also shown are three DA WD models with different effective temperatures (red lines), all of which have been normalized to match the flux of the low-state spectrum at 1480 Å. The effective temperatures of the models are indicated, with cooler temperatures yielding spectra with broader Lyman $\alpha$ features.

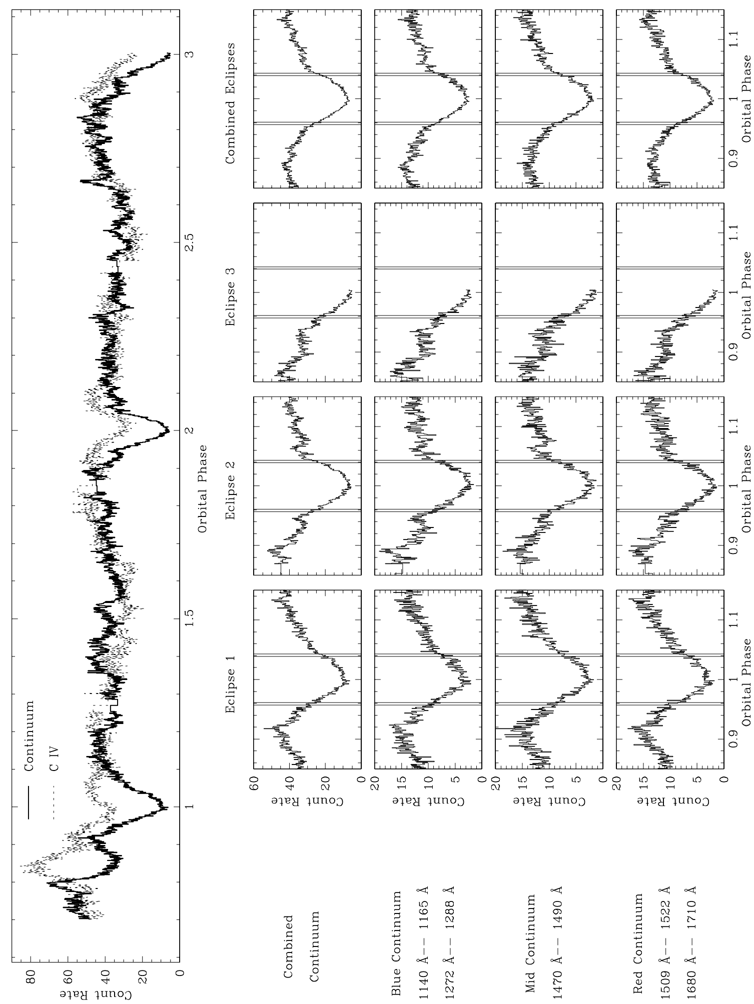


Fig. 2.— The high-state, UV light curves. The top panel shows continuum (continuous line) and C IV line flux (broken line) light curves. The three bottom rows of panels show the continuum eclipses in more detail. Each row corresponds to a particular set of continuum windows (as indicated) and the eclipses are shown individually (first three columns) and in combination (last column). The vertical lines mark the WD contact phases measured by Araujo-Betancor et al. (2003). Note that the continuum lightcurve in the top row is constructed from the summed count rates in all continuum windows.

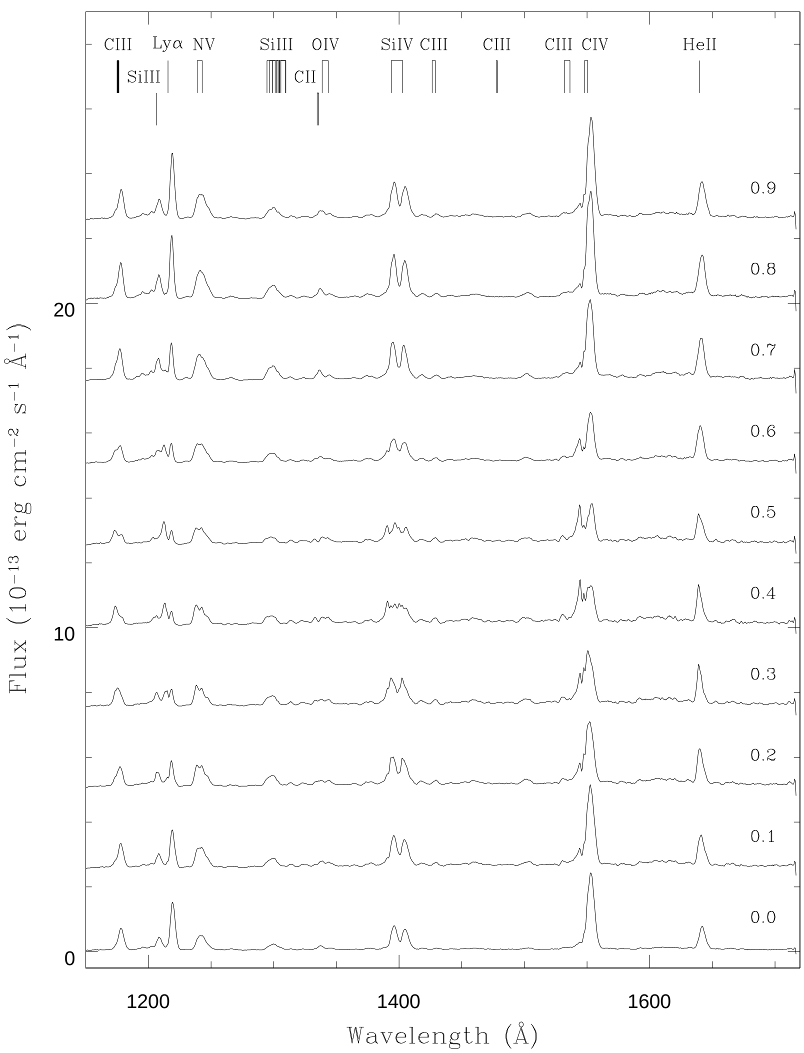


Fig. 3.— Orbital-phase binned, high-state UV spectra. Only the bottom (mid-eclipse) spectrum is on the correct flux scale, the others have been offset by multiples of 2.5 in the units of the ordinate axis. Suggested line identifications are marked, as are the orbital phases corresponding to the mid-point of each bin.